The Advanced Photon Source*

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Abstract

The Advanced Photon Source (APS) is a 7-GeV third-generation synchrotron radiation storage ring and full-energy positron injector. Construction project funding began in 1989, and ground breaking took place on 5 May 1990. Construction of all accelerator facilities was completed in January 1995 and storage ring commissioning is underway. First observation of x-rays from a bending magnet source took place on 26 March 1995. Nearly all performance specifications of the injector have been reached, and first observations indicate that the reliability, dynamic aperture, emittance, and orbit stability in the storage ring are satisfactory. Observation of radiation from the first of 20 insertion device beamlines is scheduled for October 1995. Start of regular operations is expected to take place well before the APS Project target date of December 1996.

I. INTRODUCTION

The APS accelerator systems consist of:

- 250-MeV electron linac
- 450-MeV positron linac
- 450-MeV positron accumulator ring
- 0.4 to 7-GeV booster synchrotron
- 7-GeV, 100-mA low-emittance (8 nm-rad) positron storage ring (see Figure 1)

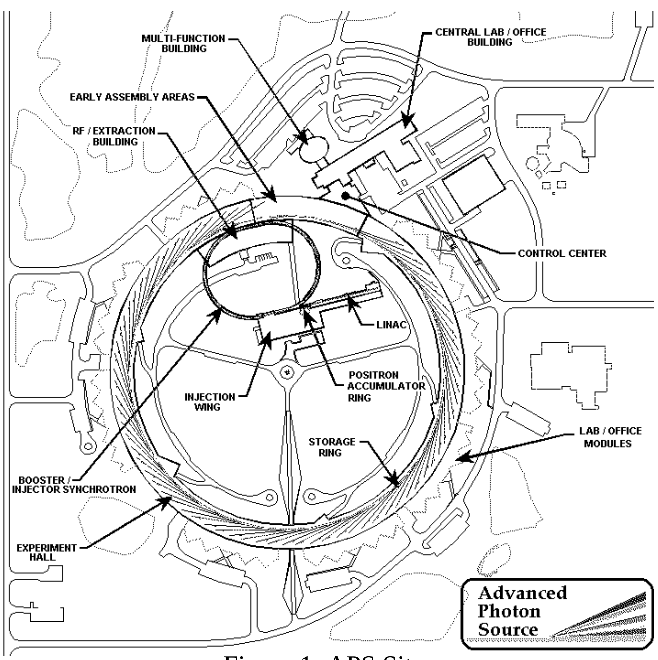

Figure 1: APS Site.

The purpose of the Advanced Photon Source (APS) at Argonne National Laboratory is to provide extremely brilliant beams of x-rays for basic and applied research in areas such as materials science, biology, and medicine. It is one of a large and growing number of "third generation" light sources [1], designed to make best use of the tuneability and monochromaticity of synchrotron radiation from undulators. At present, x-ray beamlines are being designed and constructed for 20 of the 35 available straight sections of APS by 17 collaborative access teams, or CATs. The CATs include participants from 104 universities, 37 industrial research organizations, and 16 research laboratories. Independent researchers will have access to the CAT beamlines for up to 25% of the available operating time. Protein crystallography, characterization of the structure of viruses, and x-ray microscopy are a few of the experimental capabilities of APS beamlines.

These experimental opportunities are made possible by the very high flux of photons of selectable wavelength which can be brought to bear on a sample under investigation. The quantitative measure of this intensity is "brilliance," peak 4-dimensional transverse phase space flux density of photons in a 0.1% bandwidth. The APS storage ring was designed with a Chasman-Green lattice to produce an 8-nm-rad damped emittance so as to provide high brilliance from its undulators. The 7-GeV energy and 8-mm vertical physical aperture [2] in the insertion device straight sections were chosen to enhance the tuning range of undulators. For example, APS undulator "A" [3], which will be installed in 18 APS beamlines, will produce $1\text{x}10^{17}$ to $2\text{x}10^{18}$ photons/(sec mm^2 mrad^2 0.1%bw) in the energy range 44 keV to 3 keV. Special-purpose insertion devices such as the elliptical motion wiggler [4] will provide unique additional capabilities.

II. SCHEDULE AND COST

The APS Project began in FY 1989 with funds sufficient to begin architectural design. Groundbreaking took place in May of 1990. Site preparation was completed one year later, at which point construction of the injector buildings began. Linac installation began in April of 1992 and was completed in October of 1993. Positron accumulator ring installation was completed in January of 1994, and booster synchrotron installation was complete two months later. Storage ring installation activities began in April 1993, when construction of the first segments of the storage ring tunnel was completed. Storage ring installation was completed in January of 1995.

The total construction cost of the APS is $467.2 million. Cost of construction of the accelerator systems was $150 million, with $44 million allotted to the injector, $91 million allotted to the storage ring, and the remainder allocated to common facilities and activities such as central controls, survey activities, and magnet measurement. Figure 2 depicts the funding history of the Project, as well as major milestones since 1989.

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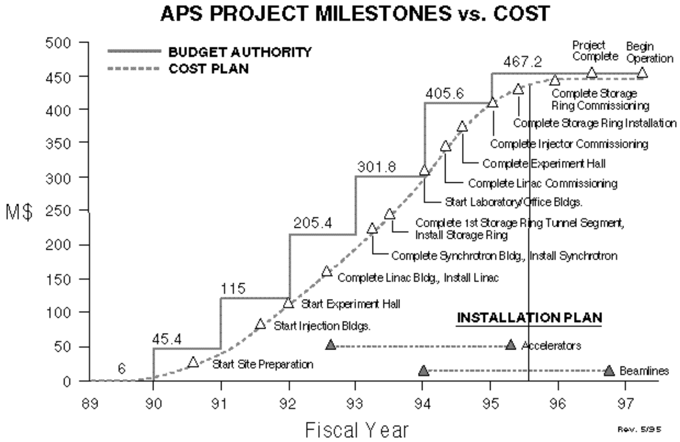

Figure 2: APS Project Budget Schedule.

III. COMMISSIONING CHRONOLOGY

Linac commissioning [5] began with the production of 50-MeV beam on 7 October 1993. The linac has supplied electrons for commissioning the downstream accelerators since January 1994, while positron production studies were pursued in parallel. Performance specification for positron current was achieved by 31 July 1994 and the specified positron energy was achieved in February 1995.

Positron accumulator ring (PAR) commissioning [6] began 27 February 1994, and stored beam was achieved 17 April 1994. The PAR has run reliably, supplying electrons for booster and storage ring commissioning since April 1994. Positron injection studies have been postponed until installation of a septum magnet capable of 60-Hz operation in June 1995.

Booster commissioning [7] began 21 April 1994. Difficulties arose with the regulation bandwidth of the ramping power supplies, causing a rather slow approach to specified performance. Acceleration to 1 GeV was achieved 24 August 1994, and 4-GeV beam was produced 18 October 1994. First 7-GeV beam was produced 22 January 1995. After extensive improvements to the power supply regulation [8,9], the booster has run very reliably at 7 GeV for storage ring commissioning since February 1995.

A 4-GeV beam was transported through two sectors of the storage ring on 30 October 1994, before installation of the ring was complete. First 7-GeV beam was delivered to the completed storage ring 20 February 1995. Commissioning proceeded smoothly [10] from first turn on 18 March to first observation of bending magnet radiation from a stored 4.5-GeV beam on 26 March 1995. Storage at 7 GeV was achieved on 15 April 1995.

IV. LINAC DESCRIPTION AND STATUS

The APS staff functioned as general contractor and final assembler of the linac. The gun was purchased from Hermosa Electronics. Klystrons are Thomson 35-MW units operated at 2856 MHz. After the vendor for the modulators went bankrupt, the linac group completely reworked the modulator design and finished construction [11]. Accelerating waveguide and SLED cavities follow SLAC design and were purchased from Schonberg Engineering. Quadrupoles and bending magnets were purchased from Danfysik.

The first accelerating waveguide of the electron linac is powered by a dedicated modulator and is followed by four more 3-meter waveguides powered by a single klystron with SLED. The electron beam is brought to a focus on a 7-mm-thick tungsten target from which 8-MeV positrons are collected for acceleration. The positron linac is essentially a duplicate of the electron linac, followed by an additional set of four accelerating sections excited by a klystron and SLED to produce 450-MeV beam. The positron production target may be retracted to allow acceleration of electrons to 650 MeV.

Almost all major performance criteria for the linac have been met, with the exception of the energy spread of the positron beam (1% desired, 1.6% measured); it is expected that optimization of focusing near the production target will yield the desired 30 nsec x 8 mA positron macropulses at 450 MeV.

V. POSITRON ACCUMULATOR RING DESCRIPTION AND STATUS

The DC magnets for the PAR were purchased from Danfysik, and DC supplies were built by Inverpower and Dynapower; pulse magnets and supplies, vacuum beam pipe, rf cavities, and amplifiers were all built to APS designs, mostly by local machine shops.

The PAR is a 30.7-meter circumference storage ring, the design of which is inspired by the positron intensity accumulator (PIA) ring; its lattice has twofold symmetry with two dispersion-free straights for rf and injection/extraction. Almost all the vertical focusing is supplied by the 25-degree edge angle of the eight zero-gradient dipole magnets. Special attention was given to clamping the end fields of these magnets to control soft-edge focusing effects.

The PAR is intended to collect 24 pulses from the linac at 60 Hz, capturing with a 1st harmonic (9.77 MHz) rf system, and finally compressing longitudinally with a 12th harmonic rf system before extraction to the booster. Because the beam from the linac has rather long macropulses, the PAR uses fluorescent flags for first-turn diagnostics rather than rf beam position monitors.

Commissioning studies have led to a very comprehensive and accurate model of PAR optics, as well as a set of convenient and powerful software tools for commissioning [12,13]. Measurements of ring properties such as corrector response matrix, dispersion function, tunes, chromaticities, rf voltage, etc. were first performed as automatic scripts which invoke the software tools; these scripts may now be used by Operations Group personnel for troubleshooting.

At present the PAR performance has been excellent with electrons. Injection tests at 30 Hz have yielded better than 95% capture efficiency. Current accumulation requirements for the PAR have been exceeded; over 190 mA of beam has been stored. Positron accumulation tests will begin in June.

VI. BOOSTER SYNCHROTRON DESCRIPTION AND STATUS

APS staff developed the design and manufacturing procedures for the booster dipoles and quadrupoles. APS also functioned as general contractor for magnet fabrication, buying copper conductor and sheet iron, and placing contracts with industry for stamping of laminations and coil winding. Dipole laminations were stacked and welded at Argonne, while other magnet laminations were stacked and welded by local industry. Final assembly was carried out by APS staff.

The booster vacuum system is an APS design, using stainless conflat vacuum seals. It has achieved 10 nT pressure.

The booster has four 5-cell, 352-MHz accelerating cavities manufactured by Interatom. They are identical to cavities used in the ESRF storage ring. The cavities are powered by a Thomson klystron and Universal Voltronics high voltage power supply.

The lattice of the booster synchrotron is a 40-cell FODO, using zero-gradient dipoles. Twelve dipoles are deleted from the lattice to create four zero-dispersion straight sections symmetrically placed around the ring. A single bunch is injected directly onto the closed orbit. The booster is designed to operate at 2 Hz, ramping 450 MeV to 7,000 MeV and back during beam accumulation in the PAR.

Booster commissioning was prolonged because the ramping power supplies had insufficient regulation bandwidth. The power supply regulators were completely reworked [8,9]. During booster operation, a computer program running on an operator console workstation modifies the ramp commands to adapt to lines changes and other environmental factors. Though the modification of the ramping regulators is not complete, at present the booster is running very reliably with negligible beam loss at injection due to power supply tracking errors.

VII. STORAGE RING DESCRIPTION AND STATUS

A standard sector (Figure 3) of the APS storage ring has ten quadrupoles, seven sextupoles, eight correctors, and nine rf beam position monitors. The magnets in a sector are supported on five girders.

Construction of the magnets of the APS storage ring followed the pattern of the booster magnets; APS personnel executed the design, procured the raw materials, and developed the manufacturing technique. Commercial vendors were given the task of manufacturing subassemblies such as coils and welded cores. Final assembly was carried out by APS personnel. The storage ring dipoles were an exception; Tesla assembled completed magnets from stamped laminations and copper conductor supplied by APS.

The magnet designs were strongly influenced by the shape of the vacuum chamber, which has an antechamber connected to the beam chamber by a 10-mm-high, 127-mm-long channel. In order to accommodate the chamber, quadrupoles were designed with no iron connecting the top and bottom yokes. For the same reason the sextupole magnet yokes are three separate pairs of poles, arranged so that there is no iron in the plane of the stored beam on the outboard side of the ring. The corrector magnet yokes are shaped like sextupoles with windings on the poles to create vertical and horizontal steering fields. Magnet quality exceeded specification [14].

Table 1: Storage Ring Parameters

Nominal Energy	7.0 GeV
Nominal circulating current, multibunch	100 mA
Maximum circulating current, multibunch	300 mA
Maximum circulating current, single bunch	5 mA
Harmonic number	1296
Natural emittance	8.2×10^{-9} m-rad
Natural energy spread, rms	9.6×10^{-4}
Bunch length, rms, natural	5.3 mm
Max energy	7.7 GeV
Circumference	1104 m
Radio frequency	351.93 MHz
Number of periods	40
Length of insertion region	6.72 m
Length available for insertion device	5.2 m
Bending radius	38.9611 m
Betatron tunes	
Horizontal	35.22
Vertical	14.30
Synchrotron tune	0.0072
Natural chromaticities	
Horizontal	-64.7
Vertical	-26.4
Maximum beta functions	
Horizontal	24.1 m
Vertical	21.4 m
Beta functions at insertion symmetry points	
Horizontal	14.2 m
Vertical	10.0 m
Maximum dispersion	0.40 m
Ring acceptance	
Horizontal	22.8×10^{-6} m-rad
Vertical	20.3×10^{-6} m-rad
Vertical acceptance with undulators	1.6×10^{-6} m-rad
Beam size at insertion symmetry points, rms	
Horizontal	0.34 mm
Vertical, 10% emittance ratio	0.09 mm
Momentum compaction factor	2.28×10^{-4}
Transition Gamma	66.24
Bucket $\Delta E/E$ (BM only)	2.8%
Damping time	
Horizontal	9.46 ms
Vertical	9.46 ms
Longitudinal	4.73 ms
Radiation loss per turn, dipoles	5.45 MeV
Bending magnet critical energy	19.5 keV
Radiation loss per turn, insertion devices, max.	1.25 MeV

The quality of the magnet alignment and ring survey [15] is very good in the storage ring and indeed in the other accelerators as well. Data analysis indicates that alignment of neighboring magnet fiducials, relative to a “smoothed” reference line, is about 90 microns in the horizontal plane and 70 microns in the vertical. Stability of the storage ring is satisfactory, with less than 2.5 mm settlement between June 1993 and

September 1994, even though construction of the APS office buildings is still in progress. Settling has decelerated in those areas removed from ongoing construction.

Five girders support the magnets in a superperiod of the storage ring: two for the dipoles and neighboring sextupoles, two for the triplets of quadrupoles adjacent to the undulator straights, and one for the high-dispersion straight. These girders are supported on wedge jacks. Their lowest frequency vibrational resonance is near 12 Hz and may be described as a horizontal rigid-body motion of the girder, with the wedge jacks beneath the girders acting as springs. This resonance will be damped by a factor of 10 by insertion of Anatrol 227 viscoelastic material beneath the girders [16]. This is expected to reduce the rms horizontal motion of the girders from values as high as 300 nanometers to 50-80 nanometers (4-50 Hz) under normal conditions. Stability of the girders with respect to vertical vibrations is very good.

The storage ring vacuum system is made up of 240 aluminum chambers extruded by Taber Metals. The extrusions were machined and bent by Ideal Tool, Inc. Vacuum seals are SMC aluminum conflats at the ends of the chambers and Helicoflex seals for the rf beam position monitor electrodes. *In situ* bakeout is possible by circulating 150° C water through the chambers. Glidcop synchrotron radiation absorbers intercept the bending magnet radiation. Each chamber has approximately 7 meters (1400 l/sec) distributed non-evaporable getter (NEG) strips installed. High-power bending magnet radiation absorbers have an additional 220 l/sec ion pump and a 1000 l/sec lumped NEG pump.

The rf transmitters in the storage ring are nearly identical to that of the booster. The storage ring cavities consist of four groups of four single cells, powered by two transmitters for 100-mA operation. At least three transmitters are necessary to attain the ultimate design goal of 300 mA at 7 GeV. Four transmitters are installed, affording one spare for 300-mA operation. The cavity design is, to a very good approximation, a 500-MHz KEK rf cavity, scaled up in dimensions to 352 MHz. Cavities were fabricated from massive OFHC copper forgings by Interatom.

Storage ring and injector diagnostics [17] include flags, loss radiation monitors, visible-light synchrotron radiation monitors, and rf beam position monitors (BPMs) for the transport lines and rings. Booster and storage ring rf BPMs can archive up to 16,000 single-turn measurements and average them for a closed orbit reading. They use AM-PM conversion to provide output signals proportional to beam position and independent of beam current. They have been extremely useful in commissioning and will be integrated in a digital global feedback orbit control system for the storage ring which will collect and distribute beam position data at 4-kHz update rate for a 200-Hz closed-loop bandwidth [18,19].

The diagnostics functions and indeed other accelerator systems have been well served by the EPICS control system. The health and growth of the EPICS user community has been an important asset of the control system's utility [20].

VIII. STORAGE RING COMMISSIONING

Commissioning activities to date have included extensive use of the rf BPM system and the independent current control of every quadrupole. The first shifts were dedicated to confirming the adequacy of radiation shielding by forcing loss of known quantities of beam at prescribed locations [21]. Measurements of the response of the first-turn beam trajectory to corrector magnets were used to identify beam optics problems such as magnet polarity errors and power supply problems, to set the integer part of the betatron tunes, and to correct the first turn trajectory.

A notable demonstration of the utility of the diagnostics, controls and application tools is shown in Figure 4. It shows the average of 40 single-turn beam position measurements using rf BPMs in the high dispersion regions of the ring, displayed as a function of turn number. The result is a real-time (1-Hz update) display of the rf capture process, used to set the correct radiofrequency and phase of the rf system. This application was written by Glenn Decker in about one hour during a commissioning shift.

Once stored beam was obtained, scripts for automated orbit correction, tune measurement and chromaticity measurement were written and run. Operation of the 1-BM bending magnet radiation beamline continued, to validate the shielding and to cross-calibrate rf BPMs and correctors against x-ray BPMs. Finally a horizontal emittance measurement was made at 1-BM, which agrees within error bars with the expected value. Vertical emittance measurements are still being analyzed; they are consistent with linear coupling below the 10% design specification.

Thus far no effort has been devoted to stacking, so all measurements have been performed with less than 0.4-mA stored beam current. Commissioning has begun before completion of *in situ* bakeout of the vacuum system, which will be continued after repair of water-to-air leaks in the chamber

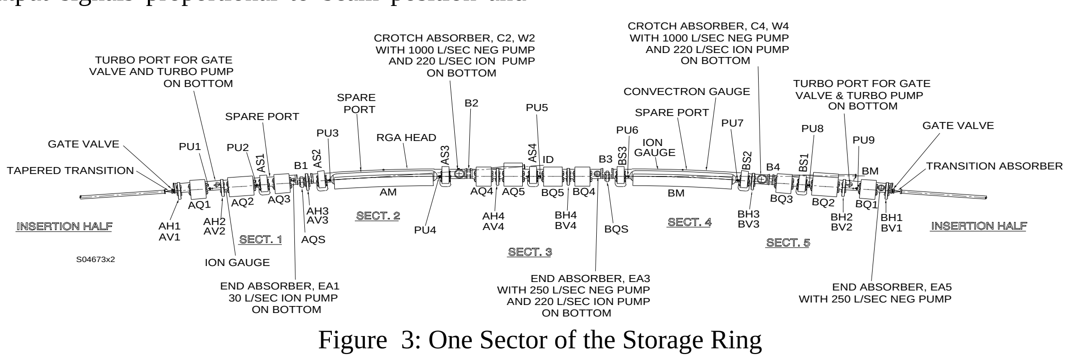

Figure 3: One Sector of the Storage Ring

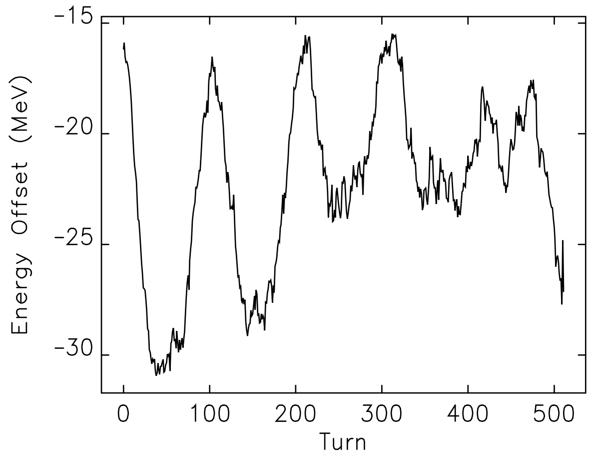

Figure 4: An operator's display of the rf capture process in the storage ring.

cooling/bake connections. For the present, the average ring pressure is about 30 nTorr, though the baked sectors have attained 0.1 nTorr. Beam lifetime at low current is dominated by the base pressure and is measured to be about six hours. The random and systematic noise of the rf BPMs was measured to be 0.25 micron/$\sqrt{\text{Hz}}$ with 300 μA stored beam. Correcting for this noise, the stability of the vertical beam position in the storage ring was measured to be 4.5 microns rms in the bandwidth 1-20 Hz. This satisfies the stability goal without use of feedback. The horizontal beam motion, at 32 microns rms 1-20 Hz, exceeds the stability target at present. Completion of installation of the viscoelastic damping material beneath the girders will bring horizontal beam stability into specification as well.

IX. FUTURE PLANS

Attempts to accumulate higher current will begin in May. Two-week commissioning periods will be separated by two-week maintenance periods through the summer, during which installation of x-ray beamline front-end components will continue and orbit stability and control will be investigated. First observation of undulator radiation is scheduled for October.

In the longer term, commissioning and machine studies will address operation with emittances down to 4 nm-rad [22], top-up operation of APS, and the limits on minimum gap of undulators in the storage ring [23].

X. ACKNOWLEDGMENT

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